16th SYMPOSIUM OF THE IAHR
SECTION ON HYDRAULIC MACHINERY AND CAVITATION
SÃO PAULO / BRAZIL
14th to 18th SEPTEMBER 1992

QUALIFICATION OF A CENTERBODY CAVITATION NUCLEI COUNTER USING OPTICAL TECHNIQUES

QUALIFICATION D'UN COMPTEUR DE GERMES A OGIVE CENTRALE PAR TECHNIQUES OPTIQUES

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Summary

A study about size measurements of cavitation nuclei is performed, by comparing results from different techniques as Holography, Phases Doppler and Centerbody Venturi. These systems are installed in line along a new installation, specially designed to guarantee optimal optical and flow conditions.
First, to calibrate the different systems, pressure distribution inside the Centerbody Venturi is determined, using Laser velocimetry measurements. Response of the optical techniques is analyzed by injecting size calibrated latex particles.
Then, the comparative measurements are performed for different cavitation nuclei conditions.

Résumé

Lors d'une campagne de mesures de dimensions de germes de cavitation, on examine les résultats holographiques, par phases Doppler et par compteur de germes à ogive centrale. Les trois systèmes de mesure sont installés en série, sur une même ligne de soutirage dessinée pour cet essai, et présentant des conditions optiques et hydrodynamiques optimales.
Au préalable, la répartition de pression dans le Venturi est déterminée par une série de mesures par vélocimétrie Laser. Puis l'injection de particules latex calibrées permet de qualifier la réponse des appareils à technique optique.
Les mesures comparatives sont ensuite effectuées pour diverses conditions de germes de cavitation.

1. INTRODUCTION

The importance of injecting nuclei during cavitation tests on models has been written about in several publications [1, 2, 3, 4, 5]. In the case of Francis models, the necessity of injecting nuclei to reach the saturation cavitation characteristic is shown, in order to be in similarity with the full-scale machine. A precise determination of the test water nuclei distribution must be made to ensure the injection of a proper nuclei content. More particularly, when determining cavitation inception, the "bigger" nuclei must be known, as they govern all the phenomenon [5, 7, 8]. In developed cavitation, a correlation should be made between model performances, cavitation developments and nuclei distributions [4, 6]. It is of major importance to determine the number of nuclei and their size with precision.

There are different measuring techniques, optical ones and hydrodynamic ones. The advantages of the optical methods are non-intrusive in-situ measurements and a relatively direct visual access to the measured particles. But, there is a problem in making the difference between solid particles and cavitation nuclei. Moreover, the final results can not be obtained in real time or will not represent the spatial mean of the nuclei characteristics.

The hydrodynamic method of the micro-Venturi, based on the same physical phenomenon that governs the cavitation development on a machine, will not count the solid particles. Moreover, with this technique, there is an advantage of measuring nuclei distribution in line and continuously during model tests, with real time results. Nevertheless, the main problem of this method is the precise determination of the dimension of the nuclei. Indeed, these values are calculated from the flow characteristics through the Nuclei Counter and its geometry. If precise measurements of the flow values can be obtained relatively easily, the inner geometry is hard to be determined. With regard to the nuclei number, the measurement is based on the detection of the collapse or the explosion of the activated nuclei through the Venturi, the advantage of the second detecting concept being the possibility of visualizing the activated particles, and then, to calibrate the number of detected nuclei by comparison with simultaneous high speed photographs [2, 3, 4].

The purpose of this study is to compare and qualify several techniques for nuclei measurements, in order to define precisely the water nuclei distribution, for accurate cavitation tests.

First, there is an attempt to determine precisely the pressure distribution in the centerbody nuclei counter, to change this instrument into a quantifying one.

Then, an experimental study is made, to compare the results from different nuclei measuring techniques, as Holography, PDPA (Phase Doppler Particles Analyzer) and a Centerbody Venturi. These systems are installed in line, along a special perspex tube with optical glass windows, to guarantee similar flow conditions. The comparison is made for different nuclei distributions and flow conditions.

2. TECHNIQUES FOR NUCLEI MEASUREMENTS

2.1 Optical techniques

The advantages of the optical methods are non-intrusive in-situ measurements and a relatively direct visual access to the measured particles. These optical techniques are based on the scattering light phenomenon. Light will be scattered when a particle is flowing across the probe area, generated by an incident light. The intensity of this scattered light is proportional to the diameter of a spherical particle, assuming that the size of the particle remains much larger than wave length of the incident light. Regarding to the limitations of these techniques, by decreasing the size of the particles, the signal-to-noise ratio will drop off quickly. At the present time, accurate measurements can not reasonably be obtained under 5-10 μm diameter particles. Moreover, it is a real problem to discriminate cavitation nuclei from solid particles and dirt.

Holography is still considered as a reference for granulometric measurements. This technique has a major disadvantage, due to the long analyzing time of the holograms.

During this experimental study, holographic measurements are made by Mr. Royer and Miss Luquet, from the Institut Franco-Allemand de Recherches de Saint-Louis (ISL). Mr. Royer, as a specialist of holographic applications [9, 10], made the analyzes of all holograms.

The Phases Doppler anemometry for cavitation nuclei measurements is now well improved. The Aerometrics system, used during this experiment (PDPA), has been studied by Mr. Bachalo in numerous publications. To obtain optimum light scattering collection angles and calibration curves for cavitation nuclei and latex particles, Dr. Gréhan from the Institut National des Sciences Appliquées de Rouen (INSA), is asked to study the system in the tests configuration. His study is based on the Lorenz-Mie Theory [11], which assumes an uniform illumination of the particles. His results [12, 13] and those of Mr. Bachalo on the geometrical optics approximation [14, 15], allow the determination of the relation between phases and spherical particles diameter.

Dr. Gréhan has studied several optical configurations and collecting angles, for two different types of particles : cavitation nuclei and latex particles. These particles are characterized with a different scattering mode : the main modes are reflection for cavitation nuclei and refraction for latex particles. A collecting angle of 45° is found to be an optimum regarding to :

- a unique relation phases - diameter,
- a good visualization of the signals,
- a good signal-to-noise ratio.

As the main result of this parametric study, precise phases-diameter relations are defined for both cavitation nuclei and latex particles. The scattering light is mainly governed by the reflection mode for cavitation nuclei, when by the refraction mode for latex particles. For the tests configuration, the useful ranges for cavitation nuclei and latex particles are under 100 µm, resp. 70 µm. Figure 1 represents the characteristic phases-diameter curves for cavitation nuclei :

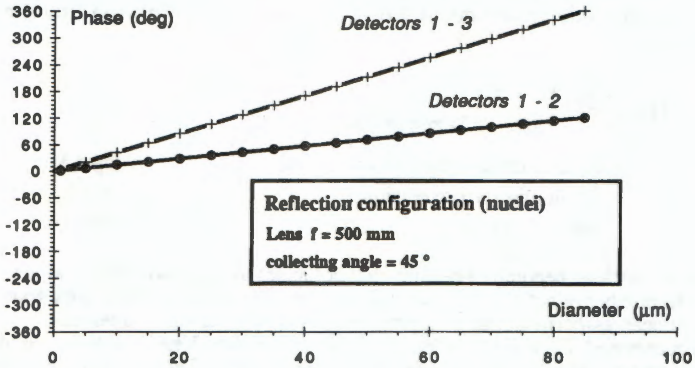

Figure 1 : Characteristic phases-diameter curves for cavitation nuclei

2.2 Hydrodynamic technique of the micro-Venturi

The hydrodynamic system used is a Centerbody Venturi with collapse detection of the nuclei (Figure 2). In this nuclei counter, the flow is accelerated through a restricted section, bound by a central conical body and a cone diffuser, in order to promote the explosive growth of the nuclei. Then, in the region where the pressure increases, the activated nuclei will collapse. By setting a controlled lowest pressure - under the vapor pressure, p_v - in the restricted section of the Venturi, all the nuclei characterized by a critical pressure higher than this lowest value, will be activated [4, 16]. Then, these nuclei are counted. The critical pressure of a nuclei corresponds to its limit of stability .

By changing the flow rate through the Centerbody Venturi, the lowest pressure can be adjusted. Its value is determined from measurements of the upstream pressure and the flow rate, and the inner geometry.

$$p_{min} = c_{p\ min} \cdot \frac{1}{2}\rho \left(\frac{Q}{S_{ref}}\right)^2 + p_{ref}$$

where S_{ref}, the reference section upstream of the restricted section, and $c_{p\ min}$ the minimum pressure coefficient along the Centerbody, are known.

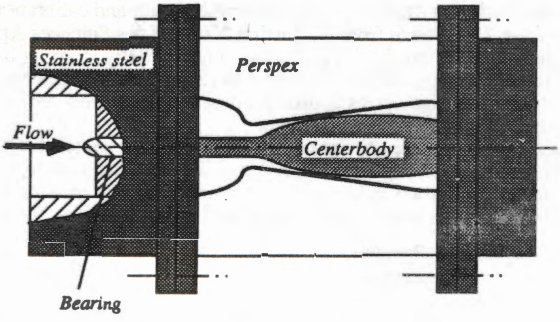

Figure 2 : Principle of the Centerbody Venturi

Then, all the nuclei with a critical pressure, p_{cr}, higher than the lowest value in the Venturi, p_{min}, will be activated. By repeating this operation for different "lowest pressure values", it is possible to determine the cumulative nuclei distribution as a nuclei spectrum function of the critical pressure, and then, function of the critical radius, Ro_{cr}. The direct relation between critical pressure and critical radius being :

$$Ro_{cr} = -\frac{3\Gamma - 1}{3\Gamma} \cdot \frac{2\gamma}{(p_{min} - p_v)_{cr}}$$

where	Γ	:	ratio of the specific heats of the gas	(c_p/c_v)
	γ	:	gas-liquid surface tension	(N/m)
	p_v	:	vapor pressure	(N/m^2)

Each activated nucleus becomes a bubble, that collapses after growth time and generates a short shock wave. The number of activated nuclei is determined by counting these shock waves, with a piezo-ceramic transducer, associated with an appropriate system for the signal treatment.

As already mentioned, the major advantage for the Centerbody Venturi is to be based on the same physical phenomenon that governs the cavitation development. Thus, it will count only the cavitation nuclei and not the solid particles. Regarding to number of activated nuclei, a calibration of a similar instrument, based on the detection of the explosive growth of the nuclei was made [2, 3, 4]. Then a comparison between instruments of both detection concepts (explosion and collapse of the nuclei) has shown a good reliability of these counting techniques.

The purpose of this study is to calibrate the size of the activated nuclei, and not the amount.

3. EXPERIMENTAL COMPARISON

3.1 Test installation

To ensure similar hydrodynamic conditions for each instrument, nuclei measurements are performed in line.

A new perspex installation with optical glass windows is designed, and the optimal conditions for each technique are taken into account. This fixes dimensions and geometry of the whole measuring line. This new installation is represented in figure 3.

In the measuring sections, the optical glass is treated (air-glass and glass-water) for the wave length of the Laser rays used during the experiments.

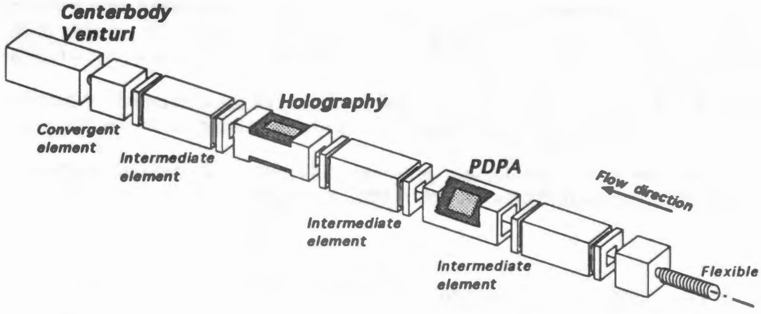

Figure 3 : New installation for comparative nuclei measurements

3.2 Calibration of the measuring techniques

3.2.1 Centerbody Venturi

The main problem for accurate measurements with the Centerbody Venturi is the determination of the "controlled" lowest pressure value at the restricted section. Indeed, critical pressure and radius of a nucleus is determined from this minimum value. Direct pressure measurements along the Centerbody is hard to carry out. In this case, it should be necessary to drill a large amount of holes along the Centerbody and the perspex cone diffuser. In addition, problems would certainly appear when connecting the tabs with the pressure transducers. Moreover, even if the tabs are very small, the flow through the Centerbody Venturi would be modified. More particularly, , the modified instrument would be no longer operational for further nuclei measurements.

Then, the pressure distribution is determined indirectly, by measuring the velocity distribution inside the Centerbody Venturi, using a non intrusive method, LDA. The measurements are not easy to carry out, as the area between the centerbody and the perspex cone diffuser is very small. But, using lenses with short focal characteristics, and optimizing the optical way of the Laser rays, it is possible to measure correctly velocity profiles along the nuclei counter.

The velocity measurements are performed for two different upstream pressure levels and two different flow values in the Centerbody Venturi, $0.9 \cdot 10^5$ N/m^2 and $2.4 \cdot 10^5$ N/m^2, resp. $0.45 \cdot 10^{-3}$ m^3/s and $0.75 \cdot 10^{-3}$ m^3/s.

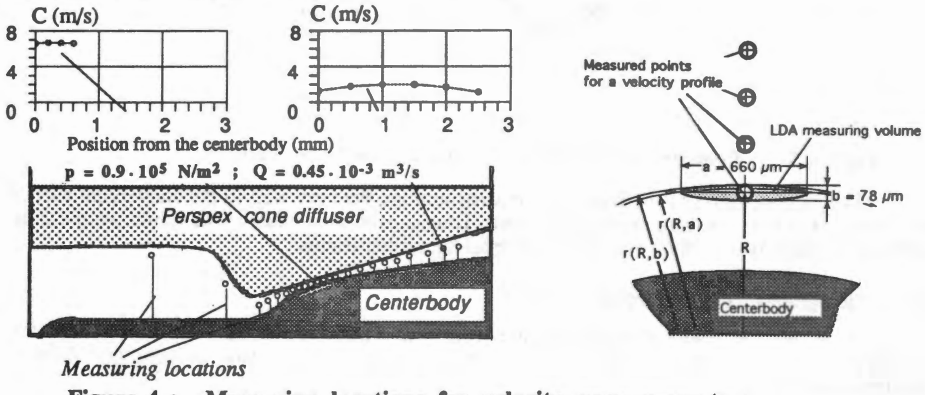

Figure 4 : Measuring locations for velocity measurements

The characteristic dimensions of the measuring volume are 78µm, resp. 660µm. The smaller dimension, being parallel with the velocity profile axis, allows the measurement in several vertical points for a given axial location (Figure 4). So, the result can be represented with a velocity profile measured along about 2/3 of the distance between the centerbody and the perspex cone diffuser. These profiles are measured for 23 locations inside the instrument (Figure 4). Two typical velocity profiles are also represented on figure 4.

An experimental study about the operating conditions of the Centerbody Venturi has shown, that the losses can be neglected in the convergent part of the instrument, from the upstream reference location to the restricted area [17].

Then, by neglecting the losses, pressure distribution is defined from the velocity measurements. It is represented in pressure coefficient, c_p, expressed as follows :

$$c_{p\,i} = 1 - \left(\frac{C_i}{C_{réf}}\right)^2$$

where $C_{réf}$ represents the upstream reference velocity, and C_i the velocity at the i location.

The purpose of this experimental study is to determine the minimum pressure value, at the restricted area. This way to define the pressure distribution, by neglecting the losses, should lead to realistic results.

To control the measurements, a calculation is carried out to verify the flow conservation along the instrument. For the low flow rate condition, a mean value of $0.45 \cdot 10^{-3}$ m^3/s is calculated from the velocity profiles, which corresponds to the flowmeter value, with a precision of ± 3 %.

The pressure distributions determined by the velocity measurements in the Centerbody Venturi are represented on figure 5, for two cases :

Upstream pressure	= $0.9 \cdot 10^5$ N/m^2	and flow = $0.45 \cdot 10^{-3}$ m^3/s,
Upstream pressure	= $2.4 \cdot 10^5$ N/m^2	and flow = $0.75 \cdot 10^{-3}$ m^3/s.

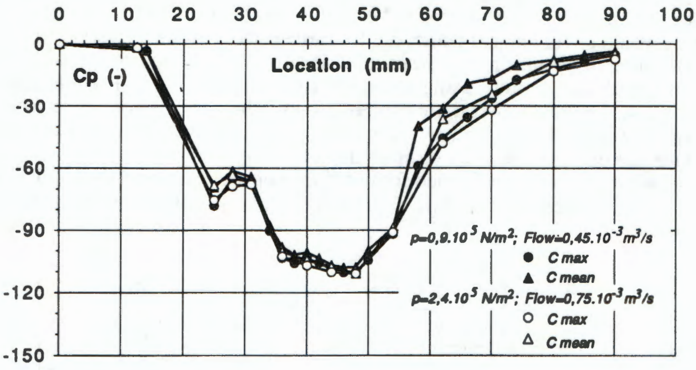

Figure 5 : Pressure distributions in the Centerbody Venturi

The superposition of the two pressure distributions fits very well in the convergent part of the instrument, where the losses are insignificant. Thus, a calibrated value of the minimum pressure coefficient is determined, which will characterize all the further results.

3.2.2 Holography - Phases Doppler

To verify the results and the response from both PDPA and holography, calibrated latex particles are injected in non-degassed water, in a closed circuit. The latex particles have the following diameter characteristics :

1.	5.002 µm	± 0.033 µm	size uniformity :	< 1.4 %
2.	9.870 µm	± 0.057 µm		< 0.8 %
3.	50.200 µm	± 1.000 µm		< 5.0 %

For the Phases Doppler measurements, the relation between phases and diameter must be changed, as refraction is the main scattering mode for latex particles (see 2.1).

Nevertheless, due to the scattering process, large cavitation nuclei could be taken as small latex particles in refraction mode, and large latex particles as small cavitation nuclei. Then, it is necessary to measure the histogram in nuclei configuration (reflection), to see if there are some large cavitation particles. If there are no latex particles larger than 70µm and nuclei larger than 100 µm, corresponding to the ranges defined by the results of Dr. Gréhan, no major problems will occur, as the phases are in opposition.

Then, both latex (refraction) and cavitation nuclei (reflection) histograms are measured with the PDPA, to know the complete water characteristic. Figure 6 represents these histograms.

The response of the PDPA against the latex injection is correct. Indeed, in "latex configuration" (refraction), 5, 10 et 50 µm particles are well detected. In "nuclei configuration" (reflection), a larger content is measured around 30 µm, the test water being non-degassed, and the content increases under 10 µm.

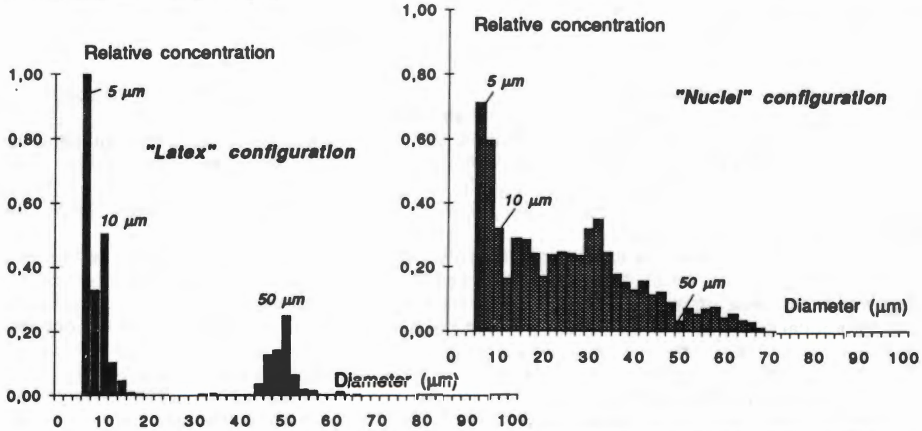

Figure 6 : Latex and cavitation nuclei histograms, measured with PDPA.

Regarding to the holographic results, it is not possible (for small particles) to discriminate latex particles from cavitation nuclei, as every spherical particle is counted. After the analysis of the holograms, the measured histogram is represented on figure 7 :

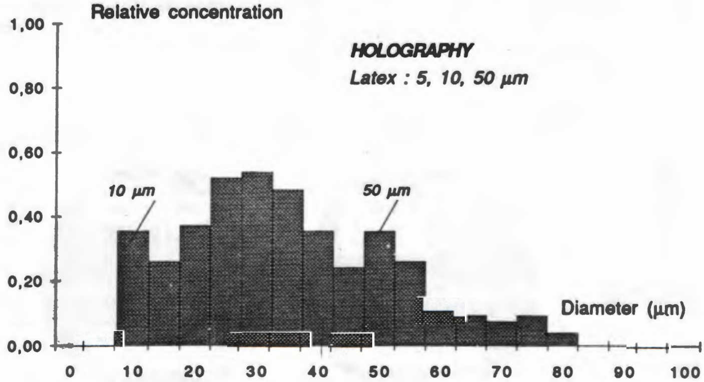

Figure 7 : Spherical particles histogram, measured with Holography

The response of the holography Technique is correct. Indeed, with the detection limits of this technique close to 5 µm, 10 et 50 µm particles are well detected. A larger content is also measured around 30 µm, as with the PDPA in reflection scattering mode.

In conclusion, for this calibration test, the histograms determined with both techniques are similar and correct.

3.3 Comparative measurements

First, the in-line installation is tested to determine the pressure and flow ranges that guarantee a correct operation, without leak of water or air suction. If such a problem appears during the comparative tests, the water sample would not be similar for each nuclei measuring technique.

Then, the in-line installation is connected to a test rig, with nuclei control. Several series of measurements are performed, with degassed water, without and with nuclei injection, for different pressure and flow levels. The demineralized test water, filtered at 10 µm, is characterized by a measured surface tension of 71 mN/m at 20° C.

3.4 Results

The results are represented in cumulative spectra, which means that a (D_i,c_i) couple of values corresponds to a concentration c_i of nuclei with a diameter larger than or equal to D_i.

The content is represented in concentration relative to the maximum value corresponding to nuclei injection. There is a major problem concerning the absolute concentration levels. Indeed, they are not comparable. For example, in figure 9, the concentration measured with the Centerbody Venturi is 1.5 nuclei/ccm larger than 10 µm. But with holography, respectively with PDPA, the values are 20, resp. 100 nuclei/ccm.

These large differences can be qualitatively explained, by the bad estimation of the real measuring PDPA volume, which depends on the detected particles position, the light intensity and the optical way to the detectors will affect the concentration value. Concentration, in this case, is referred to the theoretical probe area at the crossing of the laser rays. This area is smaller than the one the detecting system should "see". Consequently, the so-calculated concentration values are too large. Aerometrics is working actually on a systematic calibration procedure, to determine precisely the *in situ* real measuring volume. Moreover, as the measuring area is very small, the nuclei measurements are not representative to a mean spatial concentration. To overcome this restriction, the whole flow section should be scanned.

Regarding to holography results, due to the long analysis time, only the zones of the holograms containing large histograms are analyzed. Thus, the determined concentrations are not representative of a mean value, but they overvalue it. A research program for automatic hologram treatment exists, the purpose being a quicker analysis process. Moreover, even if the whole holograms are analyzed, the results will correspond to an instantaneous mean spatial value, and not to a temporal mean concentration. More particularly, some rare particles in the flow could easily be detected or not, depending on the picture recording time. To overcome this restricted possibility, numerous time-successive holograms should be recorded, and completely analyzed.

Figure 8 represents orders of magnitude for the analyzed water volumes by the different techniques, their ratio to the total volume of flowed out water, and the characteristic analyzing times.

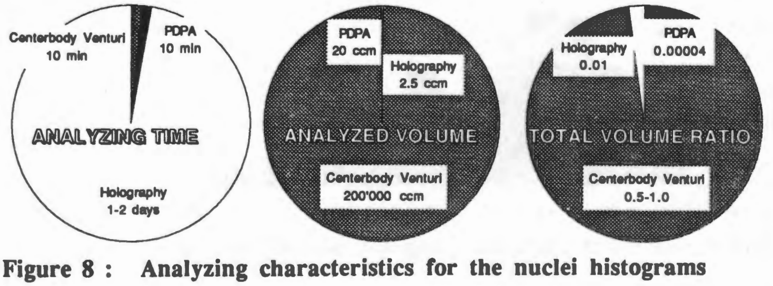

Figure 8 : Analyzing characteristics for the nuclei histograms

The nuclei distributions, in size - relative cumulative concentrations, correspond to degassed water in the test rig, without nuclei injection and with a large injection (Figure 9).

The nuclei dimension, determined with the Centerbody Venturi, corresponds to the critical value. To compare this value with the results from the other measuring techniques, the nuclei size is calculated upstream of the instrument, using a quasi-static evolution with the pressure level. As a control, a numerical resolution of the Rayleigh-Plesset equation [4], (dynamic evolution of a nuclei in a variable pressure field), shows that the quasi-static approximation gives correct results in this case.

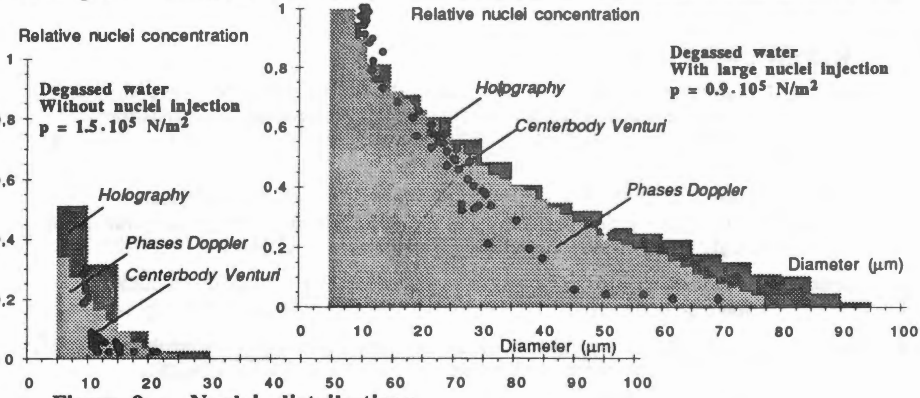

Figure 9 : Nuclei distributions.

For degassed water without injection, the larger nuclei size in diameter, measured with the Centerbody Venturi, the PDPA and holography, are respectively 23 µm, 27 µm and inside the range 25-30 µm. The critical pressure difference between 23 µm and 30 µm is about 10^3 N/m^2 (10 mbar).

With nuclei injection, the larger nuclei size in diameter are respectively 70 µm, 77 µm et 90-95 µm. The critical pressure difference between 70 µm and 95 µm is about 400 N/m^2 (4 mbar).

Thus, the characteristics of the cavitation nuclei, measured with the different techniques, are comparable and correct.

4. CONCLUSIONS

The purpose of this study is the comparison between different nuclei measuring techniques, as Centerbody Venturi, Phases Doppler and Holography, in order to determine precisely the nuclei size distribution of a test water. Regarding to a nuclei characteristic comparison (Critical pressure, critical radius), the measurements show accurate results. Thus, the goal of this study is reached, and the measured values are accurate and repetitive. Nevertheless, each instrument has its own advantages and disadvantages.

The PDPA is very easy to run and allows quasi-real time measurements of the nuclei content and their velocity. But the disadvantage of a very restricted and not well-known measuring volume does not lead to a direct spatial mean value of the nuclei content in the flow.

Holography is still a reference technique in granulometry, but it presents a major disadvantage, due to the long analyzing time of the holograms. Moreover, the mean value obtained with a hologram, does not correspond to a temporal mean concentration, as the hologram is recorded at one precise time. For these reasons, it is not reasonable to include this technique as a standard real-time process during cavitation tests.

Regarding to the Centerbody Venturi, it is necessary to determine precisely the lowest pressure value inside the instrument, to define correctly the characteristics of the detected nuclei. After a calibration of its inner pressure distribution, this nuclei counter has a major advantage, as it detects only particles governing the cavitation developments (cavitation nuclei). Moreover, it analyzes in real time the quasi-total volume of the water sample by-passed from the main flow of a test rig.

Nevertheless, this study shows a major problem concerning the measurements of absolute nuclei concentrations. Further studies will be directed in this way.

5. ACKNOWLEDGEMENTS

The author wishes to acknowledge all their colleagues from the Bassin d'Essais des Carènes, as also Miss Luquet and Mister Royer from the Institut Franco-Allemand de Recherches de Saint-Louis, Mister Bauché, who represents Aerometrics France, Mister Gréhan from the Institut National des Sciences Appliquées de Rouen (INSA), and Mister Bachalo, president of Aerometrics.

This work is supported financially by the DRET, that the author wishes to acknowledge more particularly.

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